Design and Operation of the Miniature Vector Laser Magnetometer (MVLM)

Earth Science Technology Office
Instrument Incubator Program

Contract Number: NAS5-01223
NASA COTR: Ken Anderson

Principal Investigator: Robert E. Slocum
Project Physicist: Larry J. Ryan

Polatomic, Inc.
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Company Overview

• Polatomic develops helium magnetometers for military, space, and geophysical applications.

• Business established in 1982.

• Main office is in Richardson, Texas.

• Polatomic maintains a Magnetic Test Facility (former U.S. Coast and Geodetic Survey Magnetic Observatory) at the University of Texas at Dallas.

• Multiple NASA and NAVY contracts funding development of laser-pumped vector and scalar helium magnetometers.

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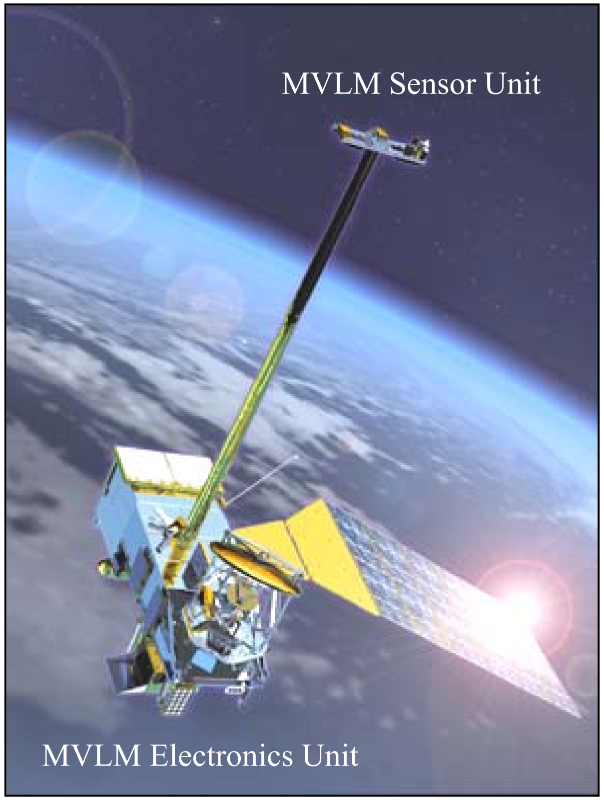
MVLM Description



- Helium magnetometer with laser pumping.
- Optically pumped He^4 in metastable triplet state.
- Capable of both vector and scalar measurements.
- Dynamic Range: ±100,000 nT
- Scalar Mode Accuracy: < ±1 nT
- Vector Mode Accuracy: < ±100 nT
- Accuracy with Self-Calibration: ± 1 nT
- Sensitivity: 10 pT / √Hz
- Sensor Unit Size: 6 x 6 x 12 cm, 0.6 kg
- Electronics Unit Size: 15 x 20 x 6 cm, 1.8 kg
- 5 W Operation, 0.5 W Standby

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Earth Science Applications

Earth’s Magnetic Field

- **Internal field** from sources within the solid Earth.
- **External field** driven by interactions with solar wind and solar radiation.

Magnetic Field Measurements

- Support models to determine geomagnetic field and its variability.
- Internal dynamics of the Earth's core
- Structure and dynamics of the lithosphere and crust.
- Interaction between Earth's magnetic field and the solar wind.
- Influences on Earth's climate.

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Helium Magnetometer Heritage

1960’s
- Mariner 4 - JPL/TI - Vector - Mars
- Mariner 5 - JPL/TI - Vector - Mars, Venus

1970’s
- AN/ASQ-81 - TI – Scalar – U.S. Navy
- Pioneer 10 - JPL - Vector - Jupiter
- Pioneer 11 - JPL - Vector - Jupiter, Saturn
- ISEE-3 – JPL – Vector - Cometary

1980’s
- Ulysses – JPL – Vector - Jupiter, Solar Polar
- AN/ASQ-208 - TI - Scalar - U.S. Navy

1990’s
- Cassini - JPL/Polatomic - Vector/Scalar – Venus, Jupiter, Saturn
- SAC-C - JPL/Polatomic - Scalar - Earth

2000’s
- P-2000 - Polatomic – Scalar - U.S. Navy
- HTG - Polatomic – Vector - U.S. Navy
- AN/ASQ-233 – Polatomic - Scalar - U.S. Navy

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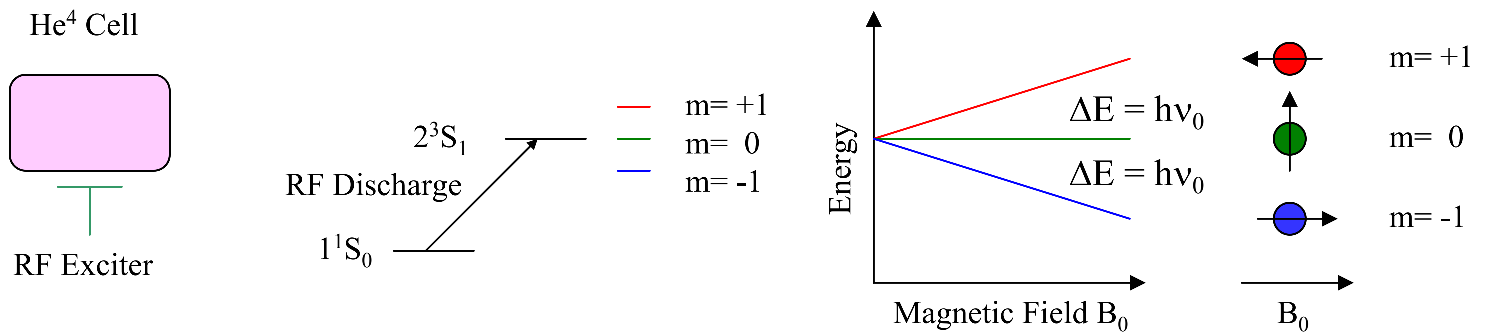
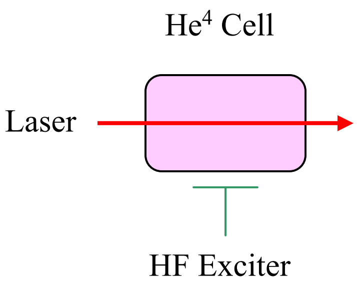
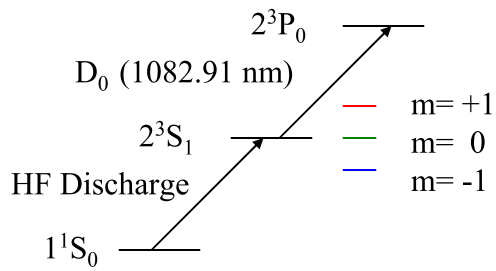
He^4 Cell Sensing Element

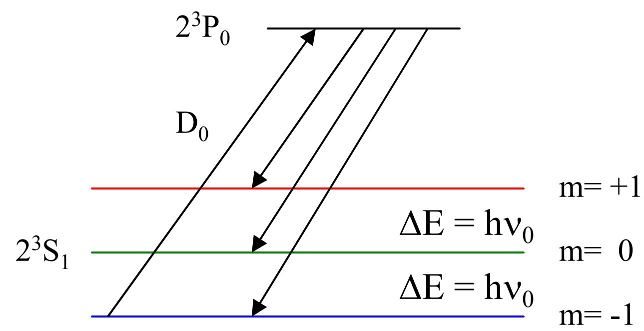


- Glass cell contains He^4 at low pressure (1.5 Torr).
- RF discharge produces metastable 2^3S_1 ground state.
- External ambient field B_0 splits energy into three Zeeman levels m= -1,0,+1.
- Separation energy $\Delta E = h\nu_0$ where $\nu_0 = (\gamma_e / 2\pi)\, B_0$ and $\gamma_e / 2\pi = 28.0249540$ Hz/nT
- Metastables in 2^3S_1 level are atomic magnets.

Optical Pumping







- Pumping produces non-equilibrium distribution of atoms among different energy levels.
- m= -1,0,+1 sublevels are equally populated in thermal equilibrium.
- m= -1 has high absorption probability for circular polarized 1083 nm laser radiation.
- 2^3P_0 atoms decay to m sublevels at equal rates.
- Laser pumping produces magnetic moment M opposite field as atoms shift to m= 0,+1.

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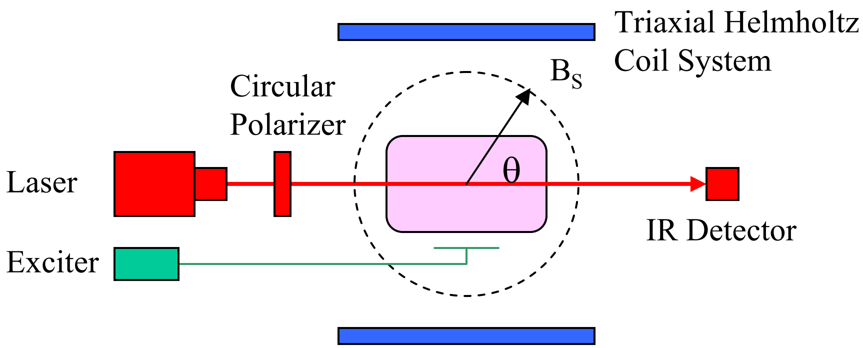
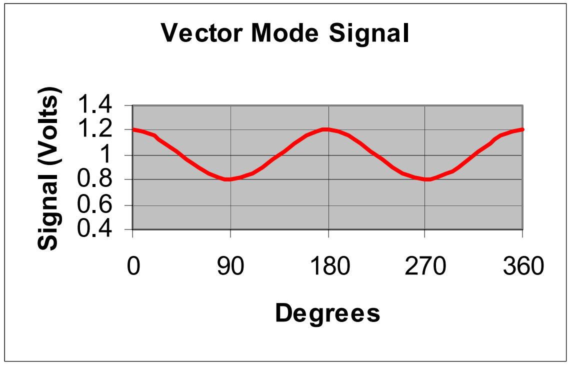
Vector Mode Operation

Bias Field Nulling (BFN)

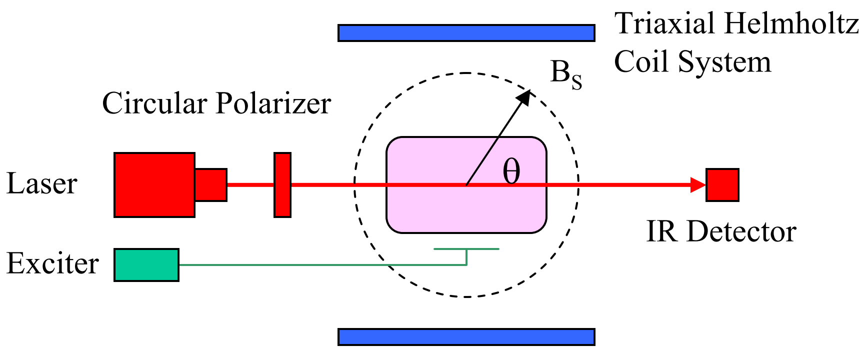


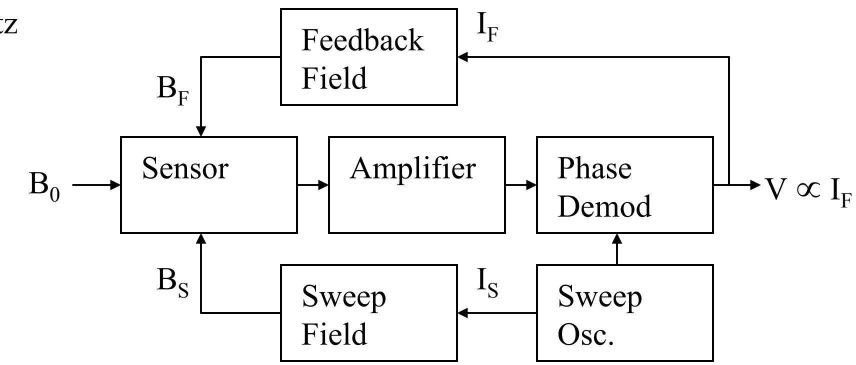


- Metastable helium subjected to circular polarized radiation and rotating magnetic sweep field B_S.
- Optical pumping efficiency and absorption depends on angle between field and optical axis.
- Absorption $\propto \sin^2 \theta$, maximum absorption at $\theta = \pi/2$ and $3\pi/2$.

Vector Mode Implementation

Bias Field Nulling (BFN)

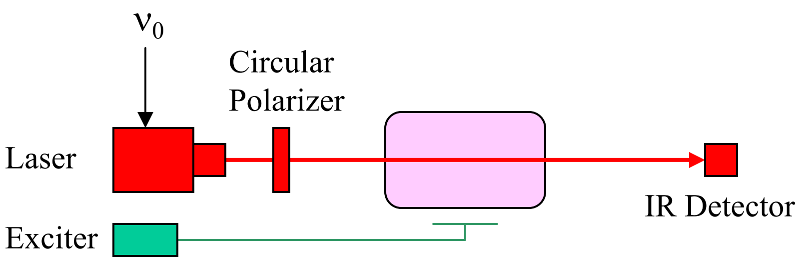


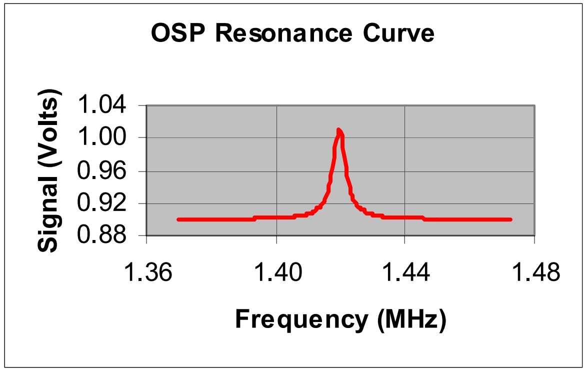


- Absorption $\propto \sin^2 \theta$.
- External ambient field B_0 causes phase shift of signal.
- Feedback steady field B_F to null ambient field.
- System maintains maximum absorption at $\theta=\pi/2$ and $3\pi/2$.
- Feedback currents I_F are a measure of the ambient field components.

Scalar Mode Operation

Optically-Driven Spin Precession (OSP)

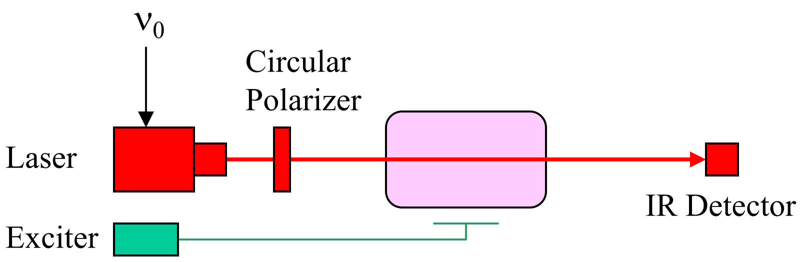


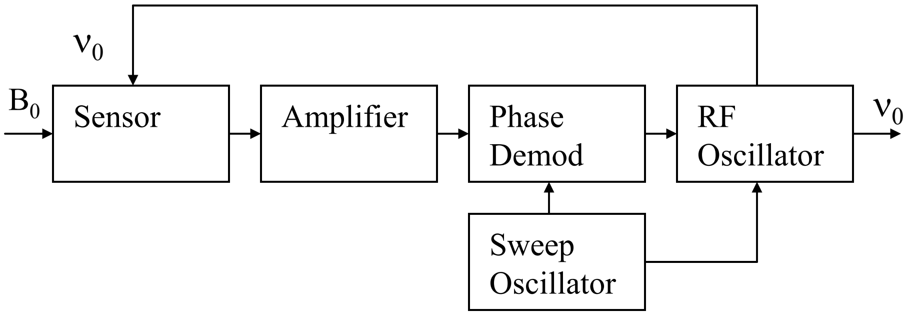


- Metastable helium subjected to pulsed circular polarized radiation.
- Optical pumping efficiency increases at resonance (Larmor frequency) ν_0 .
- $\nu_0 = (\gamma_e / 2\pi)\ B_0$ and $\gamma_e / 2\pi = 28.0249540$ Hz/nT.
- $B_0 = \nu_0 / (\gamma_e / 2\pi) = 1.42 \times 10^6$ Hz / 28.0249540 Hz/nT = 50,669 nT.

Scalar Mode Implementation

Optically-Driven Spin Precession (OSP)





- Apply periodic sweep to RF oscillator.
- Causes periodic modulation of detector output.
- Phase synchronous demodulation determines ν_0 .

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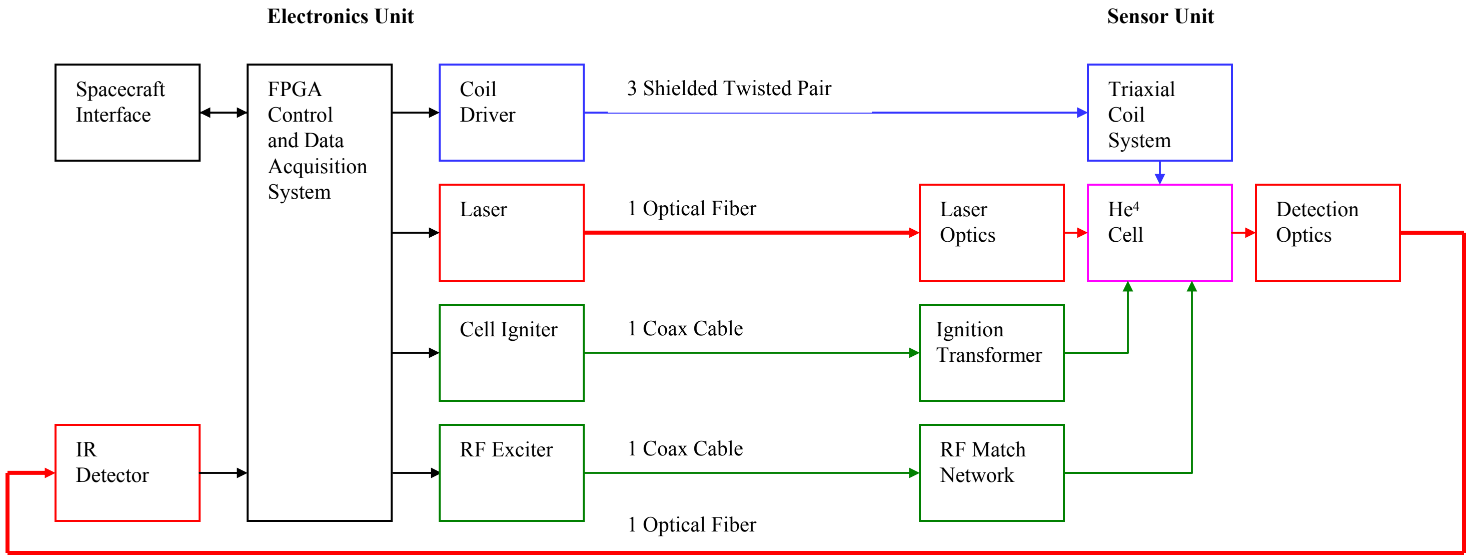
MVLM Block Diagram



- BFN vector mode and OSP scalar mode using single sensor.
- Simple design concept provides commonality between vector and scalar components.
- Sensor Unit has no active electronics.
- Component selection allowing future transition to radiation-hardened parts.

MVLM Key Technical Issues

BFN Coil System

- Effective dynamic range of 26-bits required.
- Over-sampling technique using 16-bit DAC successfully tested.

Exciter System

- Piezoelectric transformer option needs environmental testing (temperature, vacuum, radiation, reliability).
- High stability low-power RF system with air-core ignition transformer designed.

Laser Pumping System

- Laser needs environmental testing for space qualification.
- Motion of fiber causes polarization and intensity noise problems.
- PM fiber being evaluated and circular/elliptical polarization tests underway.

IR Detection System

- IR detector needs environmental testing for space qualification.

NASA Definition of Technology Readiness Levels

TRL 1 Basic principles observed and reported.

TRL 2 Technology concept and application formulated.

TRL 3 Analytical and experimental critical function and proof-of-concept.

TRL 4 Component and breadboard validation in laboratory environment.

TRL 5 Component and breadboard validation in relevant environment.

TRL 6 System prototype demonstration in a relevant environment (ground or space).

TRL 7 System prototype demonstration in a space environment.

TRL 8 Actual system completed and "flight qualified" through test and demonstration.

TRL 9 Actual system "flight proven" through successful mission operations.

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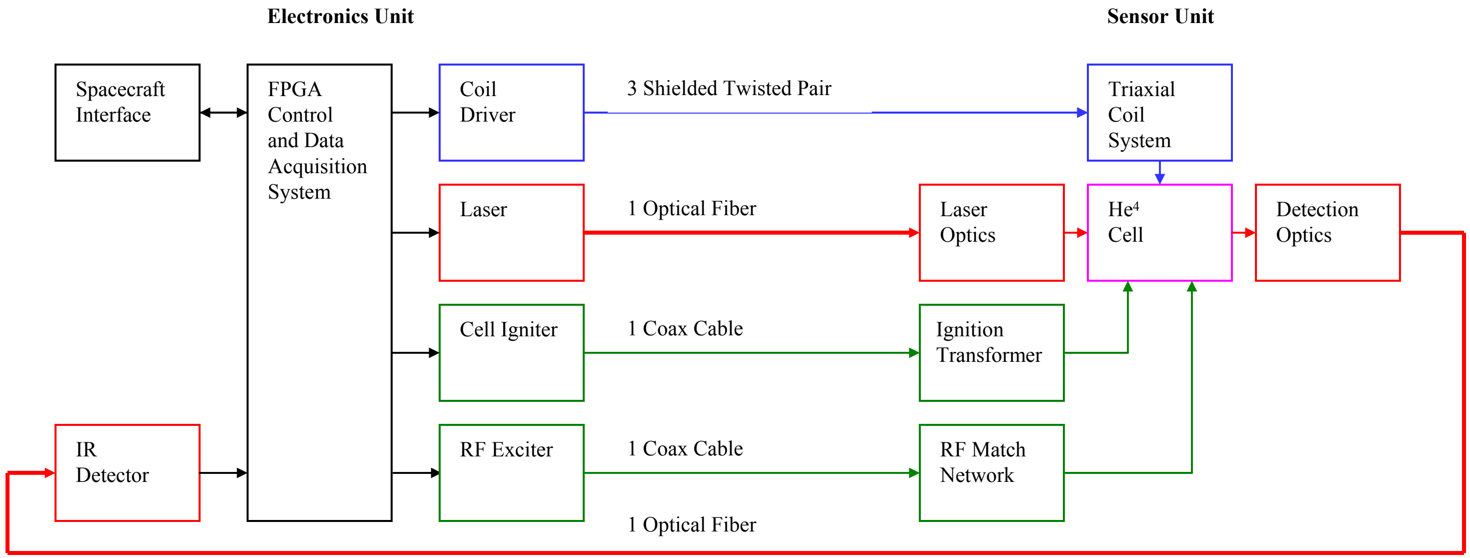
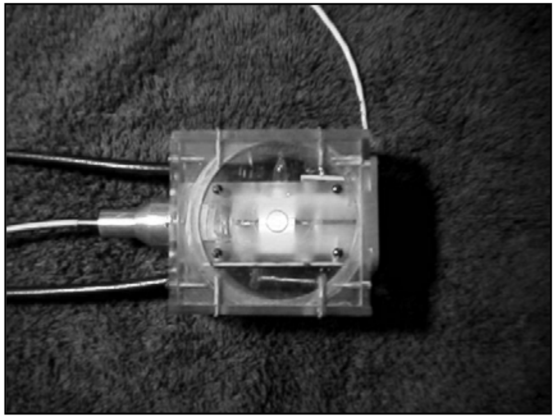
MVLM TRL Assessment Summary

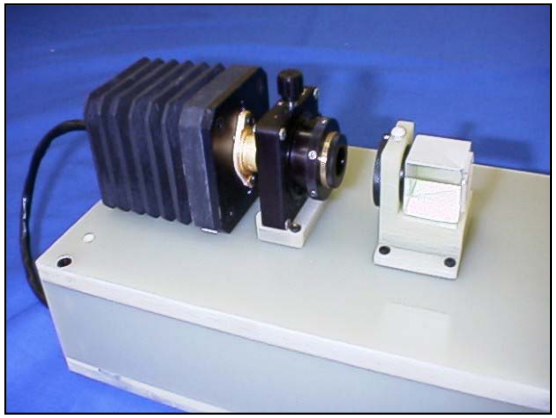


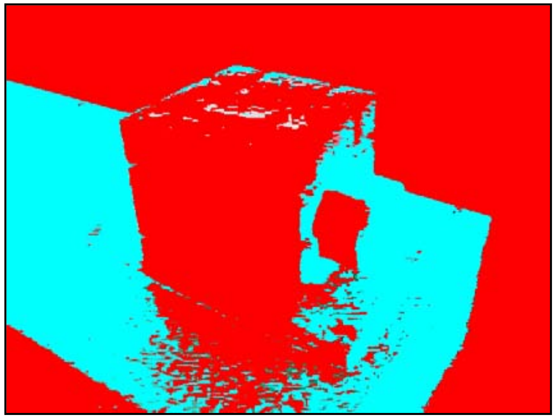
MVLM	**TRL**			
Electronics Unit	**3**	**4**	**5**	**6**
Control System		x		
Coil Drivers		x		
Laser		x		
Exciter System		x		
IR Detector		x		

MVLM	**TRL**			
Sensor Unit	**3**	**4**	**5**	**6**
Helium Cell		x		
Coil System		x		
Laser Optics	x			
Exciter Components		x		
Detection Optics		x		

MVLM Sensor Unit Breadboard Design







•Sensor Unit size is 6 x 6 x 12 cm.

•5 cm diameter coil system.

•6 cm^3 internal cell volume compared to 48 cm^3 on lamp-pumped helium magnetometers.

•Breadboard system will accept free-space optics or fiber-optics.

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MVLM Calibration Requirements

Calibration

- Nine coefficients required to calibrate vector magnetometer.
- Three offsets in absence of magnetic field.
- Three scale factors (gains) for normalization of axes.
- Three non-orthogonality angles which build up orthogonal system in sensor.

Implementation

- Vector mode measurements made using BFN technique with 0.1% accuracy.
- Scalar mode measurements made using OSP technique with 0.001% accuracy.
- Multiplex vector and scalar measurements for different sensor orientations.
- Acquire data and calculate nine calibration coefficients.

MVLM Innovations

• Single-line laser pumping permits omni-directional vector and scalar measurements with smaller cell compared to lamp-pumped cell.

• Laser allows pump source to be located in electronics unit providing further sensor miniaturization.

• Scalar mode can be integrated into instrument with no additional sensor hardware.

• Vector calibration achieved by sampling vector field components and reference scalar values in the same helium cell.

• Sensor has no permeable materials and has high radiation tolerance.

• Higher accuracy, lower offsets, better stability, and more sensitive than fluxgates.

• MVLM instrument replaces three fluxgate magnetometers and reference scalar magnetometer which reduces power, payload mass, volume, and cost .

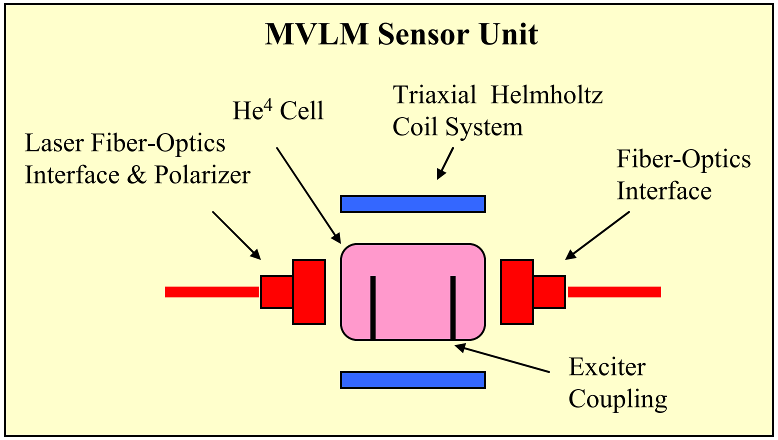
MVLM Year 2 Quad Chart

PI: Robert E. Slocum/Polatomic, Inc.

Description & Objectives

- Vector Helium Magnetometer (VHM) Design
- Laser-Pumped Miniature He^4 Cell Sensing Element
- Miniature & Rad-Hard Electronics Unit
- Dynamic Range: ±100,000 nT
- Accuracy with Self-Calibration: ±1 nT
- Sensitivity: 0.01 nT / √Hz
- Sensor Size & Mass: 6x6x12 cm, 600 g
- Power: 5 W

Miniature Vector Laser Magnetometer



Approach

- Update Flight Proven VHM Design with Laser Pump Source
- Reduce He^4 Cell Size &, Incorporate Fiber-Optics
- Utilize Scalar Mode Inherent Accuracy for Self-Calibration
- Miniaturize & Rad-Harden Electronics Unit

Co-I's/Partners

- PI: Robert E. Slocum, Ph.D., Polatomic, Inc.
- Program Manager: Larry J. Ryan, Ph.D., Polatomic, Inc.
- No Co-I's/Partners

Schedule & Deliverables

- Complete Laboratory Breadboard Fabrication…..….....Aug-2003
- Interim Review...……………………………….…….…Aug-2003
- Complete Operational Tests.………………….………....Feb-2004
- Annual Review/Final Report…………………………...Feb-2004

Application/Mission

- Airborne & Space-Borne Magnetic Field Measurements
- Earth Science & Planetary Science Missions